On-board Cloud Contamination Detection with Atmospheric Correction

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Abstract-The desirability of performing satellite, on-board science data processing and analysis, and the actual production of science data products in space is unquestionably a solution to the often discussed "data glut" problem but the roadmap to get there is rather murky. An investigation of 2 typical preprocessing algorithms, cloud masking and atmospheric correction, routinely performed during satellite data postprocessing in the Earth Sciences domain is intended to provide some insight on more sophisticated analyses. Central to the issue of real time data processing in an on-board computing environment is speed, therefore, these 2 algorithms are benchmarked on a variety of commercial microprocessors with the expectation of inferring performance on flight-qualified processors. Intuitively, a sequential processor, especially the lower performance radiation hardened versions essential to some space missions, cannot process and analyze science data fast enough to be practical in a real time, on-board environment so 2 other computing devices, the Field Programmamable Gate Array (FPGA) and the Application Specific Integrated Circuit (ASIC), which introduce some degree of parallelism, are also investigated with hardware implementations of the 2 algorithms. The embedding of these algorithms in silicon introduces additional parameters other than speed which must also be considered when approaching the issue of sophisticated on-board science processing. Gate count becomes equally important as speed since radiation immune FPGAs and perhaps to a lesser extent ASIC's are limited in design space. There is also the issue of acceptable accuracy since in situ data, conventionally required for some preprocesssing algorithms is unavailable.

I. INTRODUCTION

The "data glut" problem is often cited in the literature in conjunction with Earth Science missions. It is a by-product of multi-instrument satellite platforms and increasingly higher dimensionality data collection instrumentation. Implementing sophisticated on-board science data processing and analysis and thereby enabling the production of satellite data products in space offers a challenging solution to the "data glut" problem.

While the goal is clear, unfortunately, the roadmap for such a technological feat is rather murky. We are laying the groundwork, however, in this research, by first investigating the feasibility of performing 2 typical preprocessing algorithms associated with Earth-observing missions. It is presumed at the outset, that if none of the general categories of computing devices serving as platforms for performance testing is capable of executing these algorithms swiftly enough for a real time, on-board mode, then more sophisticated algorithms normally relegated to postprocessing on the ground are out of the question for a satellite on-board computing environment.

The two preprocessing algorithms selected are cloud contamination detection (cloud masking) and atmospheric correction. Computing devices, serving as platforms for performance testing are the microprocessor, the FPGA and the ASIC. The National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) instrument serves as the model and NOAA14 AVHRR Level 1b, 4 km Global Area Coverage (GAC) data is used as a data source. Real time applicability is determined by comparing computational speed to the AVHRR scan rate.

II. Algorithms

A. Cloud Masking

The use of remotely sensed data to derive geophysical measurements such as Vegetative Index or Sea Surface Temperature is typically hindered by the presence of cloud contamination. Multi-spectral data collections containing cloudy image pixels generally require a cloud detection procedure to mask out defined areas from further processing. The seminal work of Saunders and Kriebel [1] in the arena of cloud detection was loosely used as a foundation for the formulation of spatial coherence analysis and thresholding techniques for cloud identification which collectively analyzed all 5 NOAA14 AVHRR channels. For day scenes, the following algorithms were applied: Infrared Threshold Test, Spatial Coherence Test, Visible Threshold Test, Near-Infrared to Visible Ratio Test and the Thin Cirrus Test. These tests were preceded by 3 background tests corresponding to surface conditions that might result in misclassifications by the cloud tests: Sunglint Test, Snow/Ice Background Test and Desert Test. These 3 tests were extracted from the Phillips Laboratory, Automated Satellite Cloud Analysis – Tactical Nephanalysis (TACNEPH), Air Force Materiel Command document [2]. For night scenes, the Infrared Threshold Test, Spatial Coherence Test, Fog/Low Stratus Test, Medium/High Level Cloud Test, and Thin Cirrus Test were applied.

Specific tests (or options within a test) were invoked depending on the time of day of the observation (day or night) and the underlying surface condition (sea, land or coast) at the time of satellite overpass. A global land-sea mask with a resolution of 1/16 degree provided surface condition information (coastal areas were inferred at the land – sea boundaries). The time of day was based on the computation of the solar zenith angle. "Night" was assigned to those image pixels with solar zenith angles greater than 85 degrees.

The choice of algorithms was partially based on manageability, albeit at the expense of accuracy, Very sophisticated algorithms of high accuracy which could be tested on microprocessor platforms would have a small likelihood of achieving a hardware implementation, at least, within the allotted timeframe. While sacrificing accuracy, beginning with something simpler and fundamental was expected to result in algorithms likely to be implementable within FPGA and the ASIC microcircuits.

In some cases, even the fundamental cloud masking algorithms have undergone simplifications in order to tailor them for a simulated on-board computing environment and to facilitate a hardware realization. Generally, large databases and histogram analysis was avoided as was the benefit of in situ data. For example, for the Infrared Threshold Test without the benefit of mean Sea Surface Temperature (SST) or forecast surface skin temperature, this test used instead a fairly stable 270 degree Kelvin reference temperature over Sea [3] and over Land, a computed global mean monthly surface temperature estimate for the base period 1880 to 1999 [4], which disregarded geographic location. Saunders and Kriebel's [1] classical Spatial Coherence Test which calculated a standard deviation applied to a sliding window of 3x3 pixel arrays was replaced, for the sake of an easier FPGA implementation, by an alternate local uniformity test of Thiermann and Ruprecht as discussed by Cracknell [5]. As a further simplification, sub-pixel analysis was not performed, the only 2 classification categories were CLOUDY or CLEAR.

The general scheme for cloud detection for day scenes was to first run through the 3 background tests. If CLEAR SNOW or CLEAR DESERT was detected then no further cloud tests were attempted for that target pixel. If SUNGLINT was detected then subsequent cloud tests were skipped over with the exception of the spatial coherence test because of its insensitivity to sunglint [3]. As with day scenes, cloud tests were run sequentially on night scenes on a pixel by pixel basis. When a test produced a positive result (cloud detected) further cloud testing for that target pixel was aborted.

B. Atmospheric Correction

The corruption of surface target information acquired by a satellite sensor due to the intervening atmosphere is well documented. The mechanisms which alter the directional properties of solar radiation and give rise to its attenuation as well are attributed to scattering and absorption. The most dominant of the two is atmospheric scattering and it is this phenomenon that is addressed by Chavez's dark object subtraction algorithm [6] which he applied to Landsat Multi-Spectral Scanner (MSS) and Thematic Mapper (TM) data. This algorithm has been adapted for AVHRR GAC, again sacrificing accuracy by making a number of simplifying assumptions in order to make this research task manageable within the allotted time frame.

Since scattering is inversely proportional to wavelength, only the 2 visible AVHRR channels are atmospherically corrected by the Chavez algorithm [6], the effects on the thermal channels being less dominant. The dark object subtraction (or haze correction) technique assumes that probability dictates the existence of some number of dark pixels within a satellite image which might arise from water bodies, dense dark vegetation or topography. A histogram technique is employed to identify this offset or starting haze value (SHV) for AVHRR Channel1 (CH1) and then the offset is subtracted from the DN value for every CH1 pixel. The algorithm then relies on a relative scattering model (a power law function) to predict the Channel2 (CH2) haze value to which a gain and offset correction is applied. The amplitude of the SHV is used by Chavez [6] to identify the power law relative scattering model. Chavez's SHV amplitude ranges were adapted for AVHRR by proportionately scaling them according to the relative DN dynamic range of Landsat [0 – 255] and AVHRR [0 – 1023] data. This gross assumption obviated the need for a separate study which would have had to correlate AVHRR CH1 amplitudes with Chavez's 5 relative scattering models [VERY CLEAR, CLEAR, MODERATE, HAZY, VERY HAZY].

III. Computing Devices

Typcally, flight computers are sequential microprocessors with varying degrees of radiation immunity depending on the mission objectives. From performance testing of the cloud masking and atmospheric correction algorithms on various commercial microprocessors we hope to gain insight on typical flight processor performance of comparable Million Instructions Per Second (MIPS) ratings. To the extent of testing to date, the following microprocessor platforms have been utilized for performance testing: Pentium III PC (500 MHZ), Sun Ultra 10 Workstation (440MHZ), and the PowerPC 750 (233 MHZ).

Intuitively, performance on a sequential processor is not expected to meet the real time demands of on-board processing; therefore, testing includes 2 additional categories of computing devices: an Annapolis Microsystems Firebird (VIRTEX) FPGA PC plug-in board (1,000,000+ gates) and a radiation-hardened general purpose programmable pipelined ASIC processor (referred to as a Reprogrammable Data Path Processor) under development at Goddard Space Flight Center. The anticipated advantage of these 2 additional platforms is the speed advantage of hardware (which naturally introduces parallelism) over serial software execution.

By introducing a silicon implementation of the 2 algorithms in question, new issues for consideration of on-board applicability arise. Prior to obtaining a silicon solution, the required gate count for the design is unknown which is the reason for selecting such a large capacity commercial FPGA microchip (no effort was made to estimate gate count). In practical application, for a space mission, due to radiation hardness requirements, the available number of equivalent logic gates is far less than commercial counterparts. However, a hardware implementation of these preprocessing routines at least will dictate a minimum design space for comparable-complexity algorithms and the state of radiation hardened technology will then determine on-board applicability.

IV. Performance and Accuracy Testing

To date, performance testing has only progressed as far as microprocessor platforms and accuracy measurements have only been performed for the cloud masking algorithm. Initially, the computational part of both preprocessor algorithms are timed, exclusive of Input/Output (IO) interfaces. Since a single scan line of low resolution GAC data represents approximately one fifth the number of samples of High Resolution Picture Transmission (HRPT) AVHRR, the execution time was scaled up by a factor of 5 then divided into the number of scan lines for the GAC data set under test. This provided an equivalent execution speed in terms of scan lines of HRTP processed per second which could then be compared with the AVHRR scan rate of 360 scans per minute [6] or 6 scans per second.

To perform accuracy measurements of the cloud masking algorithm, cloud contamination detection was observed as basically a classification problem similar to thematic classification of remotely sensed data into land use/land cover categories. Just as Congalton [8] constructed an error matrix to evaluate thematic classification, an error matrix consisting of only 2 categories, CLOUDY and CLEAR, was constructed for cloud classification which became the launching point for further analysis. Cloud masking obtained from the NOAA Clouds from AVHRR (CLAVR) algorithm was used as the reference.

V. Experimental Results

Three NOAA AVHRR GAC data sets, each containing land and water bodies, were used for testing. One data set represented a night scene and the other two, day scenes, the first with minimal sunglint condition and the second with extensive sunglint. Only the day scenes applied to atmospheric correction. Of the 3 microprocessors tested, only the PowerPC 750 which had a performance rating estimated at 400+ MIPS came even close to low-performing flight-qualified computers, the best being the BAE Systems RAD750 (300 MIPS). For many Goddard Earth and Space missions, the performance rating of selected flight computers falls under 50 MIPS; therefore, it was found that test results from the powerful Pentium III PC and Sun Ultra 10 microprocessors were not even relevant. For the PowerPC 750, it was found that the cloud masking algorithm was processed at an equivalent rate between 6 – 9 times faster than data was being scanned in. In the case of atmospheric correction, the ratio rose to 80 – 120 times faster. Overall cloud masking accuracy, with respect to the NOAA CLAVR experimental algorithm, varied by as much as 68 – 89 percent across the 3 data sets.

VI. Conclusions

A MIPS survey of typical flight computers was conducted which included the following: Honeywell GVSC 1750A, Synova Mongoose-V R3000, BAE Systems RAD6000, Honeywell RHPPC and the BAE Systems RAD750. For a flight-qualified processor to execute cloud masking in real time, assuming that remotely sensed data is scanned in at a rate no greater than the AVHRR scan rate, of those flight computers surveyed, only the RAD750 would even have a chance of executing the algorithm without data overflow. With a computational execution less than 10 times faster than data collection, this does not allow much margin to increase algorithmic sophistication to improve accuracy, let alone add additional science data processing and analysis algorithms. Therefore, a hardware solution becomes a necessity. Chavez's [6] fundamental atmospheric correction for scattering however, executed on the PowerPC with a minimum 80 times faster than necessary certainly proved to be viable for on-board execution.

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